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LASER DIAGNOSTICS OF METALLIC PLASMAS

AD A094564

Period Covered: November 1, 1978 - October 31, 1980

David R. Bach

Don Kania

James J. Duderstadt

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The major objectives of this research project were to study the X-ray emission and dynamical behavior of exploded aluminum wire plasmas when subjected to intense CO_2 laser radiation. The laser system, based on a Lumonics 601 TEA laser, was optimized to produce a diffraction limited spot size (diameter 125 microns)

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THE UNIVERSITY OF MICHIGAN

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Final Report

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The major objectives of this research project were to study the X-ray emission and dynamical behavior of exploded aluminum wire plasmas when subjected to intense CO_2 laser radiation. The laser system based on a Lumonics 601 TEA laser was optimized to produce a diffraction limited spot size (diameter 125 microns) yielding a focused intensity of 10^{12} W/cm^2. The principal X-ray diagnostics consisted of two foil measurements using filtered photomultiplier detectors. These measurements were augmented by a variety of electrical and optical diagnostics to determine the time evolution of the exploding wire and the effects of laser irradiation. Interaction experiments were performed with a radial, one sided illumination at the plasma midplane. The data obtained in these experiments is discussed and analyzed in the report.

10 to the 12th power W/sq cm

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INTRODUCTION

Exploding wires have been studied for years as X-ray sources or as sources of high density plasma for laser-plasma interaction experiments. The steep density gradients (10^{20} cm^{-4}) and high peak electron densities (10^{18} - 10^{19} cm^{-3}) of exploding wire plasmas place severe requirements on diagnostic techniques. Since exploding wire plasmas of high energy density are usually quite irreproducible, a premium is placed on performing all measurements of interest in a single shot.

Previous activities in our laboratory have been directed at developing a variety of optical and infrared diagnostic methods, including holographic interferometry, laser light scattering, and beam reflection and transmission measurements.

Of most interest in the present set of measurements are the X-ray emission characteristics of these plasmas in the soft X-ray range (100 to 5000eV). Suitable X-ray diagnostic methods have been developed, and these measurements-have been correlated with other optical and electrical measurements as with the results of coupled radiation-magnetohydrodynamic computer code models. The exploding wire apparatus has been modified to accept solid wires of aluminum as the primary target material.

In this report, the essential features of the experiments are described, and the experimental results are presented and described.

II. BACKGROUND

Previous investigations (Ackenhusen, 1977) into plasma X-ray emission have been conducted in our laboratory using lithium exploding wire plasmas. A pilot study was made with a single detector (filtered photomultiplier) on lithium exploding wire plasma. The detector was rather slow and insensitive but indicated that X-rays could be detected and their emission correlated to a dI/dt dip and streak camera indications of pinching of the wire. No emissions could be detected from the bulk plasma at times other than pinch. In an attempt to delve deeper into the development of X-ray diagnostics for the study of plasmas and laser-plasma interactions, a completely new metallic exploding wire device was constructed that was used to produce aluminum plasmas. The higher Z of aluminum would certainly increase the continuum emissions and possibly add line emissions in the X-ray region if high enough temperatures could be reached.

The current investigation included a study of an aluminum exploding wire plasma and then the interaction of high intensity CO_2 laser radiation with the plasma. The aluminum plasma was examined by a large array of diagnostics: optical, electrical, and X-ray. A specific time into the exploding wire evolution was selected as a useful time for a laser interaction experiment, i.e. temperature, density, and cylindrical symmetry were measurable. At this time a detailed study of the interaction of a high powered CO_2 laser as a function of laser energy was done. Specifically, the sensitivity and time resolution of the filtered photomultiplier measurements was drastically improved and spatial resolution of X-ray emissions was included with a pinhole camera.

III. EXPERIMENTAL DEVELOPMENT

All laboratory plasma sources possess a characteristic energy source, medium for conversion to a plasma, and external environment to allow plasma formation. An exploding wire is no exception, the power source is a single capacitor, the vacuum system supplies the necessary environment and the wire loader provides the solid aluminum wire for conversion, i.e., electrical energy stored in a capacitor is dumped into a solid aluminum wire in vacuum, voilà an aluminum plasma.

ENERGY SOURCE- a single 14μf capacitor (Sangamo, 35nH, 20kV) charged to 15kV is the energy storage medium. Transfer of the energy to the wire is through a pin triggered spark gap (See Figure I). The pin is fired by a 5C22 circuit which may be externally triggered.

VACUUM SYSTEM- Environmental conditioning is supplied by the vacuum system. The experiment is performed in vacuum for several important reasons. One, the absence of background gas during explosion prevents shunting of the discharge by this material reducing efficient energy transfer to the wire. Two, the x-ray diagnostics would cause an energy dependent attenuation of the signal that would be strongly influenced by the residual gas and, therefore, difficult to account for. Three, during laser interaction experiments the formation of breakdown plasmas in the focusing beam would make high irradiance experiments impossible. The vacuum system provides a pressure less than 10^{-7} Torr with 5×10^{-6} Torr used as a typical operating pressure. Approximately every 20 shots, the interior of the system was cleaned to remove residue plated on the vacuum chamber walls from the discharge.

WIRE LOADER- To facilitate experimental operation the ability to reliably reload straight wires is highly desirable. A wire loader was designed and built to allow a straight wire to be reloaded externally and placed accurately. External reload is very important to facilitate the acquisition of large amounts of data.

Using this apparatus, 50 μm diameter high purity aluminum wire was exploded in 2.5 cm lengths for the entire experimental run. The malliability of high purity aluminum prevented the use of more than 8 shots per load and ruled out the use 25 μm high purity aluminum at all. In pilot work done with 25 μm tungsten, a very stiff material, it was found that more than 12 shots per load could be used. In essence, the stiffer the material the more reliable the loader and more shots per load. The exploding wire system is pictured in Figure I.

DIAGNOSTICS:

Diagnostics are required to measure the parameters of the exploding wire plasma. Diagnostic data is rarely in a form that is directly useful and one must have models to interpret the data. Therefore, it is important to develop theoretical models which provide insight into experimental data. All diagnostics and theoretical models used in the present experiment are outlined below.

ROGOWSKI COIL

An inductive pickup or Rogowski Coil can be used to measure the plasma dI/dt and this signal can be passively integrated to measure I(t). Also, dI/dt may be used to determine R, L, and C parameters for the RLC circuit model of the plasma evolution and used to search for indication of plasma pinching.

PHOTODIODE

A PIN photodiode was focused on the wire midplane. The purpose of this diagnostic was to search for correlations in light output and dI/dt fluctuations, i.e., evidence of pinching. It was also used to search for indications of enhanced optical emission due to the laser interactions. Finally, it served the purpose of synchronizing image converter camera (ICC) with the ICC monitor output.

IMAGE CONVERTER CAMERAS

Two model 1D TRW Image Converter Cameras (ICC) were used to monitor the spatial origins of optical emissions from the plasma. One camera was used in the framing mode, producing 2 dimensional pictures that are exposed for a 50 ns at 200 ns intervals for 5 frames. The other camera was used in streak mode, for which a one dimensional image of the optical, plasma emission is recorded continuously in time for durations from 500 ns to 10 μs with a temporal resolution that is 1% of the streak duration. The slit width was 1mm and the streak length was 50 mm.

The magnification in the streak and framing modes was measured using an illu nated reference card in the object plane. The respective magnifications are: $M_{st} = 0.7$ and $M_{frame} = 0.3$. The spatial resolution of the framing camera is limited by the image converter tube to 16 linepairs/mm. The streak mode resolution is again limited by the camera tube but only one dimensional information is required and this is averaged across the width of the one millimeter slit.

X-RAY DIAGNOSTICS

Three types of resolution are required in our x-ray diagnostics: 1) spatial, 2) temporal, and 3) spectral. In these experiments, an x-ray pinhole camera is used to discern the spatial origin of x-radiation and a pair of filtered photomultipliers (FPMs) is used to obtain temporal resolution and gross spectral information.

X-RAY IMAGING - PINHOLE CAMERA

Imaging in the soft x-ray region of the spectrum, ($E_{photon} >$ 500 eV) required the use of methods other than the familiar refractive lens. An x-ray pinhole camera was designed and constructed.

The pinholes were constructed in our laboratory down to a diameter of 500 μm and purchsed from Edmund Scientific for small diameters. The camera body could be opened to air with the chamber at reduced pressure; the beryllium filter (12.5 μm) was sufficiently strong to act as a vacuum interface. The beryllium foil also acted as a block to visible light, passing only photons with E $>$ 500 eV. Kodak No-Screen medical x-ray film was used exclusively in the experiments because of its high sensitivity and because much work has been done on understanding its response to soft x-rays.

FILTERED PHOTOMULTIPLIERS

To obtain temporal and spectral information on plasma x-ray emissions a "two foil method" was employed. This method was first employed by Jahoda, et. al. in 1960 to determine plasma temperatures in Scylla. The method may be demonstrated by an idealized example (Ackenhusen, 1977). Assume that we have two x-ray detectors that have identical linear response to x-rays as a function of energy. In front of each detector we place a different filter-foil. Foil one transmits all photons which an energy greater than E_1 foil, two performs identically except that its cut-off is at E_2 greater than E_1. Finally, we assume that we may describe the plasma emissions in this region as a decaying exponential, dependent on the plasma temperature alone

$$\phi(E) = exp(-E/kT)$$

Therefore, to within a constant we may write either detectors output as (i=1,2)

$$O_i = C\int_{E_1}^{\infty} \exp(-E/kT)\,dE$$

which is a function of temperature alone. Unless an absolute calibration is available with details of the plasma state. A single measurement is useless because C is unknown. By using the ratio of two identical detectors there is no need for an absolute calibration. This ratio will be a function of temperature alone as can be seen by the equation:

$$R(T) = \frac{\int_{E_1}^{\infty} \exp(-E/kT)\,dE}{\int_{E_2}^{\infty} \exp(-E/kT)\,dE}$$

This may be inverted to yield

$$kT = \frac{E_2 - E_1}{\ln R}$$

The plasma temperature is thus found as a function of an experimentally measured R and tabulated foil characteristics without the requirement of any plasma density information. Two such foil-filtered scintillator-photomultiplier detectors have been built for our measurement.

FPM DETECTORS

The filtered photomultiplier detectors (FPM) consist of an x-ray filter, plastic scintillator, photomultiplier tube (PMT), and high voltage supply. Though simple in concept, the design of the detectors pictured involved great attention to detail due to the extremes of the operating environment.

FILTERS

Throughout the experiment a variety of filters were used. For further reference the filters will be referred to by their major element constituent and nominal thickness in microns. The areal density was calculated via mass and area measurements.

TEMPORAL RESPONSE

The time response of the FPM is a convolution of the scintillator and PMT response times. To estimate the net response time one takes the square root of the sum of the squares of the full width half maximum (FWHM) response to a delta function input. The FWHM response of the scintillator is 3.2 ns and that of the PMT is 4.0 ns, i.e., a net FWHM of 5.0 ns.

CALCULATIONS

To interpret the output of the FPMs it is necessary to understand the energy dependent response of the detector and one needs a model of the plasma emissions. A computer code, CROSSSECTION+RATIO, has been developed to calculate the cross sections, responses, and ratios for the material used in the experiment.

IV. LASER SYSTEM

In Figure 2 a schematic of the entire laser system is presented. The system may be divided into three parts: the laser, laser beam diagnostics, and the laser focusing system pictured in Figure 2.

The laser is a commercial unit built by Lumonics, Inc.* a model 601. It is a transverse excited atmospheric pressure (TEA) carbon dioxide laser (CO_2) operating at $\lambda = 10.6\,\mu m$. The temporal shape of the pulse is triangular with a FWHM of approximately 40 ns. Superimposed on the triangular pulse is a high frequency component corresponding to mode beating in the resonator cavity. Peak energy in the pulse was 17 J.

The optical system of the laser was diffraction limited and produces a beam pattern characteristic of unstable resonator optics. The beam area is 54 cm^2 and at a power of 400 MW the output intensity was 0.05 $J/cm^2/ns^{1/2}$ (Steel, 1976). To adjust the amount of energy delivered to the focusing optics a propylene attenuator cell was used.

A direct measurement of the intensity distribution at the focus of the germanium f/5.2 lens was undertaken. It is reasonable to assume that at least 50% of the energy is contained in a 125 μm diameter focal spot at the best focus.

ALLIGNMENT

Allignment is critical in these experiments to be sure that the laser strikes the plasma at the specified point

*Lumonics, Inc. Kanata, Ontario, Canada

and that the diagnostics are imaging that region. The interaction region was confined to the wire midplane. Optical diagnostics could be focused to this point by loading a wire and illuminating its midpoint with a HeNe laser. Both ICCs can be placed in focus mode, the image converter tube turned on continuously, and the optics adjusted until a suitable image is obtained on a ground glass plate in the film plane. The photodiode could be aligned in a similar manner by placing the focused HeNe spot on the active region of the photodiode.

The alignment of the pinhole camera was not as stringent as the FPMs due to the large area imaged. It could be aligned with a HeNe laser with the beryllium filter out of place. It was necessary to remove the camera body to replace the filter, but alignment marks were sufficient for proper alignment.

V. EXPERIMENTS

Two sets of experiments have been performed: 1) a study of the evolution of the exploding wire and 2) measurements of laser heating of the exploding wire plasma as a function of laser energy. The experimental arrangement is shown in Figure 3.

Measurements made on the plasma without laser heating had two major aims: 1) to determine the state of the plasma, and 2) to find out how long the plasma remained cylindrically symmetric such that it presented a suitable target for a laser plasma interaction and FPM ratio measurements. All experiments employed electrical, optical and x-ray diagnostics (see Table 1).

TABLE 1

Diagnostic	Quantity Measured
Rogowski coil	dI/dt
Photodiode	Plasma visible emissions
Streak camera	r(t)
Frame camera	Plasma symmetry
FPM	X-ray emissions

Once a suitable time in the plasma's evolution was characterized as suitable for a meaningful laser-plasma interaction, a set of experiments was performed to study laser heating of the plasma and to search for evidence of non-linear processes driven by the laser.

VI. DATA ANALYSIS AND INTERPRETATION

The aluminum exploding wire formed an integral part of the discharge circuit. By examining the Rogowski signals, the long term ($t > .5\ \mu s$) evolution of the plasma could be fitted to an RLC circuit model. The circuit parameters are

$$L = 200\ \mathrm{nH}$$
$$C = 13.4\ \mu F$$
$$R = .028\ \Omega\ .$$

Using these parameters one can calculate that approximately 180 J of energy are absorbed by the plasma in 2.3 μs, the time when $dI/dt = 0$. By passively integrating the Rogowski signal the current flowing through the plasma as a function of time may be ascertained. The current may be related by an equilibrium "snow plow" model temperature: (Leonard, 1972). For aluminum with an initial linear density N of 1.2×10^{18} particles/cm (50 μm diameter aluminum wire) and a linear mass density of 5.5×10^{-5} g/cm. This model states

$$I^2 = 200 nkT - 100 M r_p \ddot{r}_p$$

where I is the instantaneous plasma current, r_p the plasma diameter, and $\ddot{r}_p$ its second derivative. The plasma diameter and its derivative were measured from streak photographs of the plasma. The temperature calculated in this way is only a very approximate figure, direct measurement is much more accurate.

One and two dimensional time resolved optical images of the plasma were used to determine at what time the plasma became asymmetric azimuthally. At approximately 2.0 μs after current initiation distinct indications of asymmetry could be seen in the plasma column. These effects were verified by asymmetries noted in time resolved x-ray measurements taken from two detectors 180° apart. Up to this time it is obvious that plasma is indeed symmetrical, lending meaning to a two-foil measurement taken by two spatially separated x-ray detectors. At this stage, the plasma forms a suitable target for laser interaction. It should be emphasized that no evidence of plasma pinching has been observed in these experiments in the first 2 μs.

A further check of the plasma temperature was done with a two-foil measurement using 12 μm beryllium and aluminum filters. This data could be cross checked with the ball park calculations of the snow-plow model.

With all of the above information, a time 900 ns after current initiation was selected for a laser interaction experiment. This gave a symmetric plasma with the following properties

$$\bar{n}_I = \text{average ion density} = 1.2\text{x}10^{18}/\text{cm}^3$$

$$T_{SP} = \text{snow plow temp} = 10 \text{ eV}$$

$$T_{x\text{-ray}} = 20\text{eV}$$

At these temperatures and densities the average ionization is slightly greater than 3 (Salzman & Krubbien, 1978) yielding an average electron density of about $4\text{x}10^{18}/\text{cm}^3$.

We note that this is a highly collisional plasma. The electron and ion collision times are

$$\tau_e = 1.3\times10^{-12}\text{sec}$$

$$\tau_i = 1.4\times10^{-9}\text{ sec}$$

which should indicate good absorption of laser radiation by inverse bremsstrahlung.

LASER - PLASMA INTERACTION

Interaction experiments were performed with radial, one sided illumination by a CO_2 laser ($\lambda = 10.6\,\mu m$) at the plasma midplane. The incident energy was varied from 1-20 Joules. No major hydrodynamic perturbations of the plasma were noted in Rogowski, streak, or photodiode data at the time of the laser interaction, i.e., no hydrodynamic instabilities were driven by the laser and any heating may be attributed to the laser. These interactions were studied with the FPMs using a variety of x-ray filters: beryllium, aluminum, nickel, and copper. The pinhole camera was used to image the interaction region with a 25 μm beryllium filter.

A distinct x-ray pulse coincided with the laser pulse is evident in the FPM signals. These pulses followed the triangular shape of the laser pulse very closely in time. (see Figure 4) A sample plot of detector output versus laser energy is shown in Figure 5.

It is obvious that lasers can be used to heat aluminum exploding wires. At the high intensities encountered, (10^{12} W/cm^2),no non-linear processes seem to be occurring. No high energy photons are seen and no saturation in heating is observed. One might attribute laser absorption completely to inverse bremsstrahlung. The absorption coefficient is

$$K = \frac{\omega_p^2 \nu_{ei}}{c\omega(\omega^2 - \omega_p^2)^{1/2}}$$ (Dawson, et.al., 1969)

where ω_p is the electron plasma frequency and ω is the laser frequency, ν_{ei} electron ion collision frequency.

$$\omega_p = 5.6 \times 10^4 n_e^{1/2} = 1.1 \times 10^{14} \text{ RAD/s}$$
$$\omega = 1.8 \times 10^{14} \text{ RAD/s}$$
$$\nu_{ei} = 5.6 \times 10^{-12}/\text{s}$$

and the corresponding absorption length for the present plasma conditions is

$$\ell = 1/K = 100\mu m$$

Inverse bremsstrahlung absorption is very effective and may account for much of the absorption in the plasma.

We have also noted that the laser and x-ray pulses exhibit similar temporal evolution. This implies that energy is conducted away from the focal volume very quickly. Several processes may be involved in this process 1) hydromotion, 2) thermal conduction, 3) ionization, 4) radiation. A simple argument can demonstrate the importance of hydromotion. The speed of sound in the plasma is 1.5×10^6 cm/sec and the focal spot is the characteristic length that is important. The time scale for hydromotion is

$$\frac{r_{FOCAL}}{C_s} = \frac{100\mu m}{1.5 \times 10^6 cm/s} = 7ns$$

A specific estimation of thermal conduction is difficult as a result of the non-linear nature of the problem, but one would expect that initially the thermal wave time scales would be faster than the hydrodynamic time scales. Radiation and ionization energy losses would be occurring continuously. Pinhole pictures, time integrated, indicate that the plasma formed by the laser is much larger than the focal volume. This implies that energy flows out of this volume and into the neighboring plasma.

In conclusion, it is possible to heat aluminum exploding wire plasmas with CO_2 lasers. The interaction shows no evidence of stimulated processes and it seems plausible that inverse bremsstrahlung may account for much of the heating. The magnitude of any temperature rise is limited by energy conduction away from the focal volume.

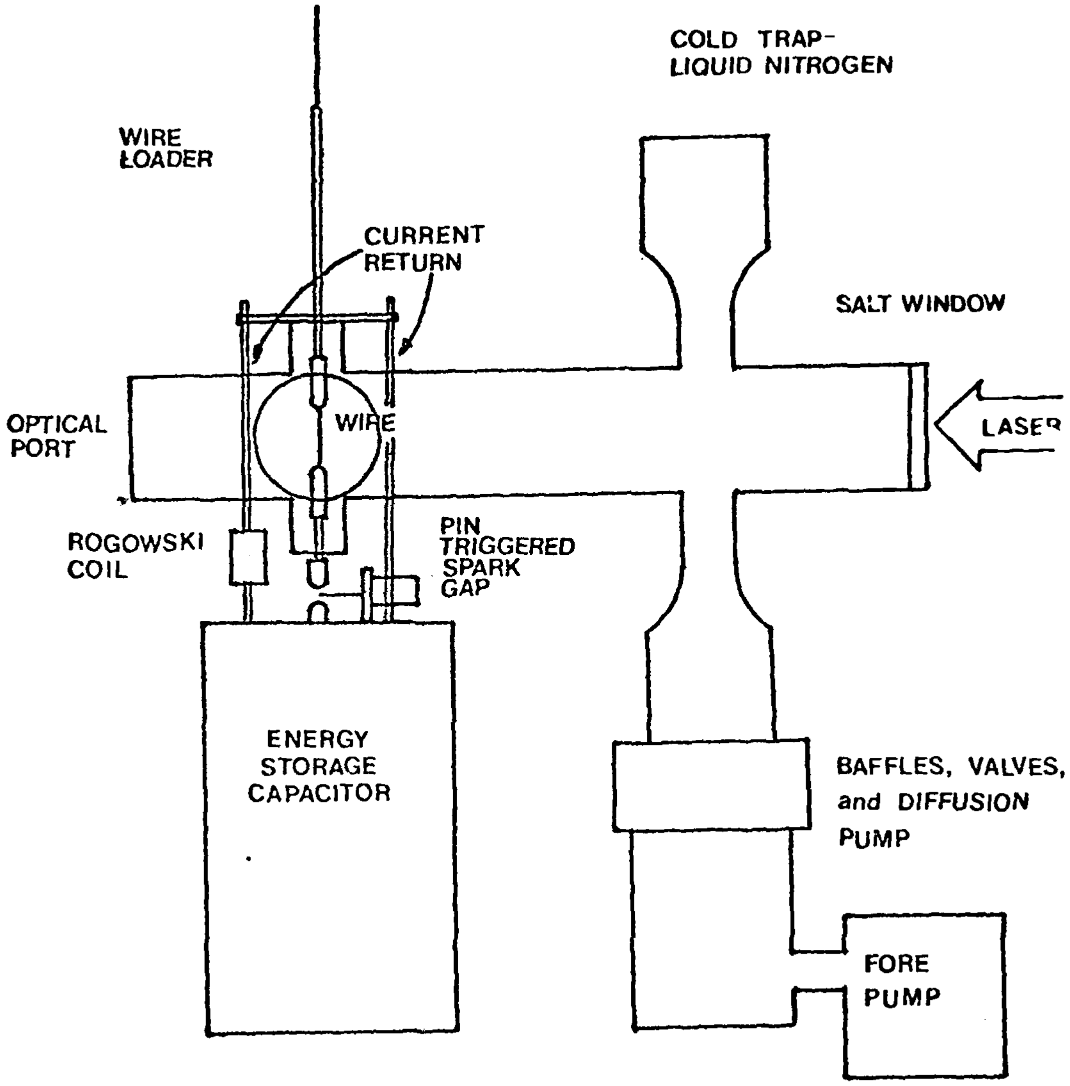


Figure 1. Exploding Wire Apparatus

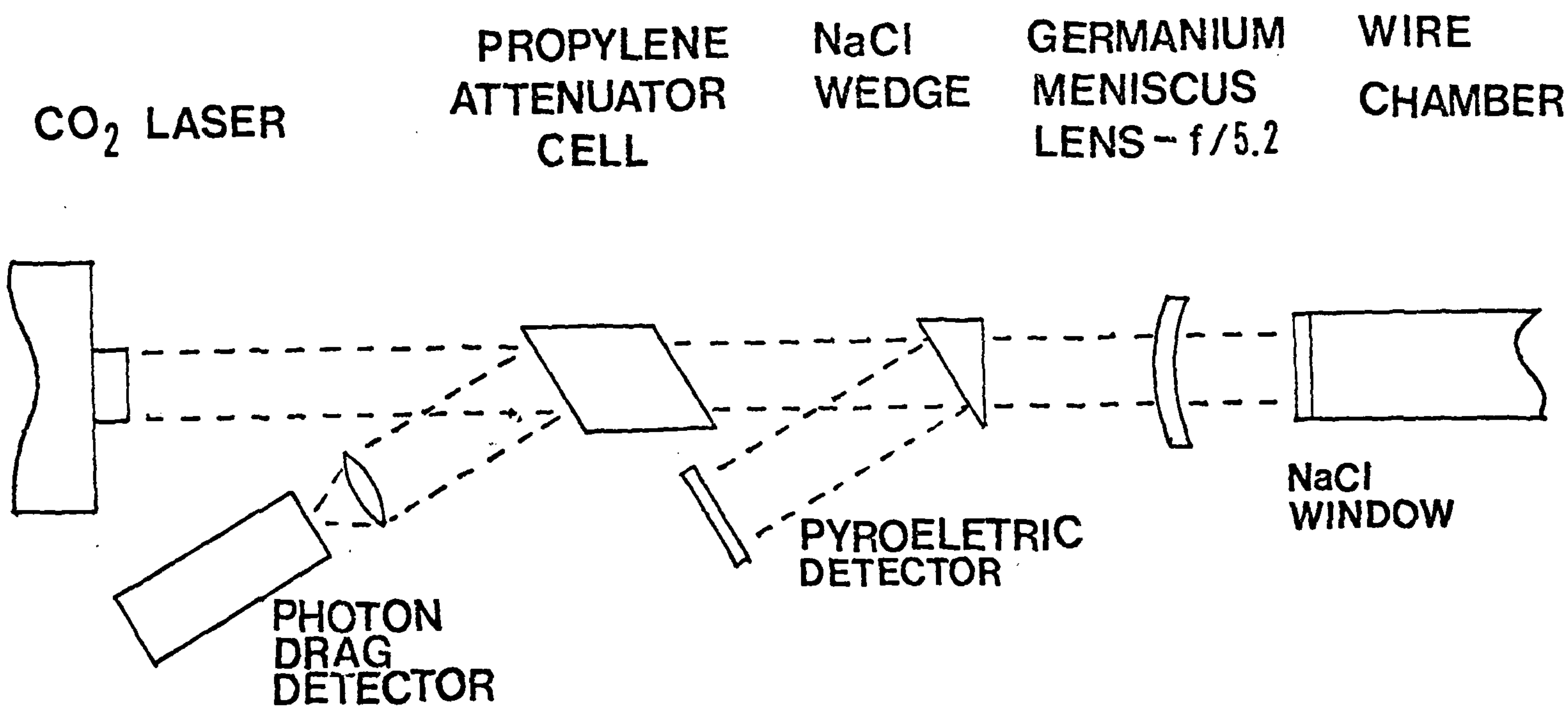


Figure 2. CO_2 Laser System

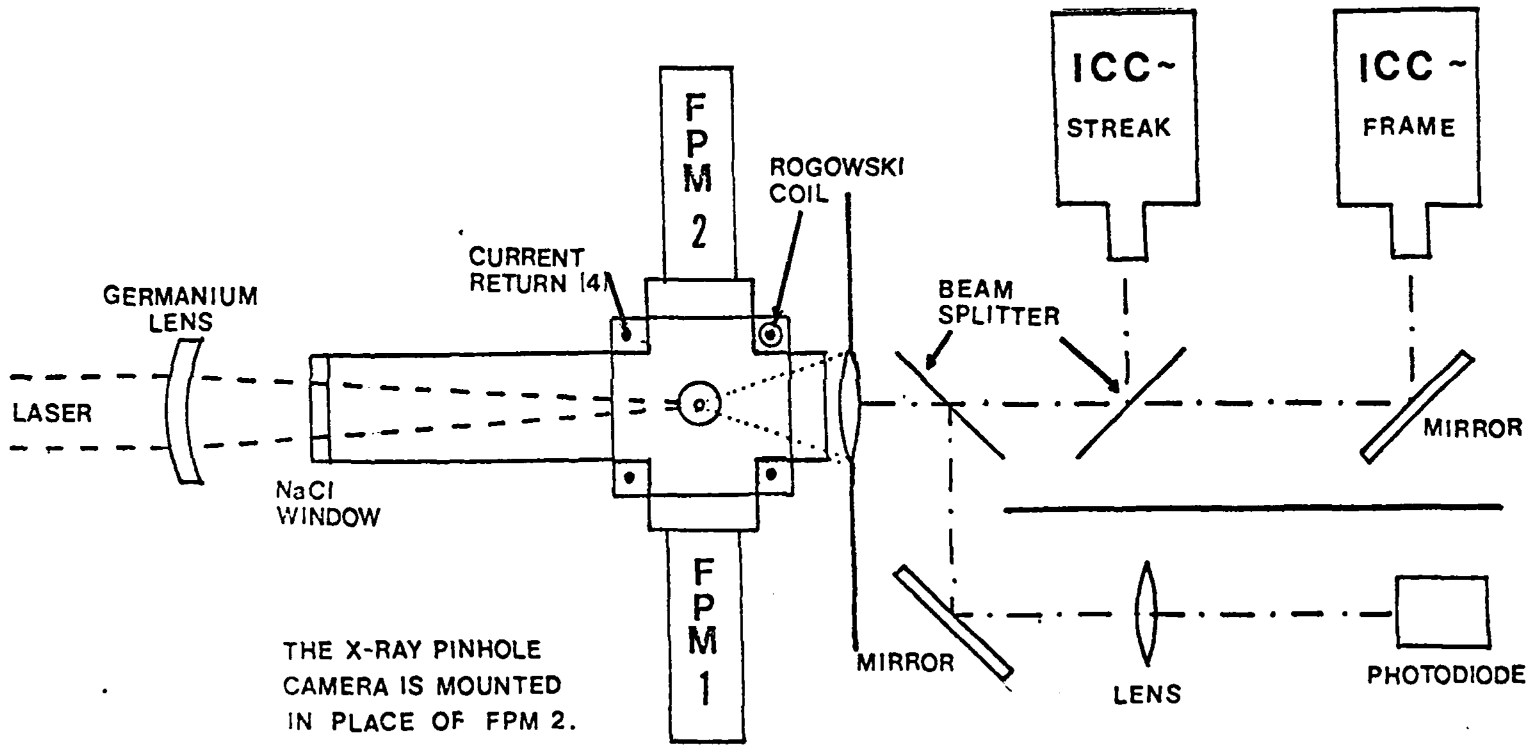
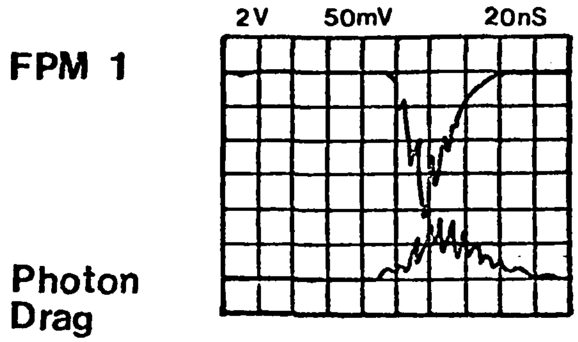


Figure 3. Diagnostic Overview



Pulse comparison:

X - Ray

CO_2 Laser

Figure 4

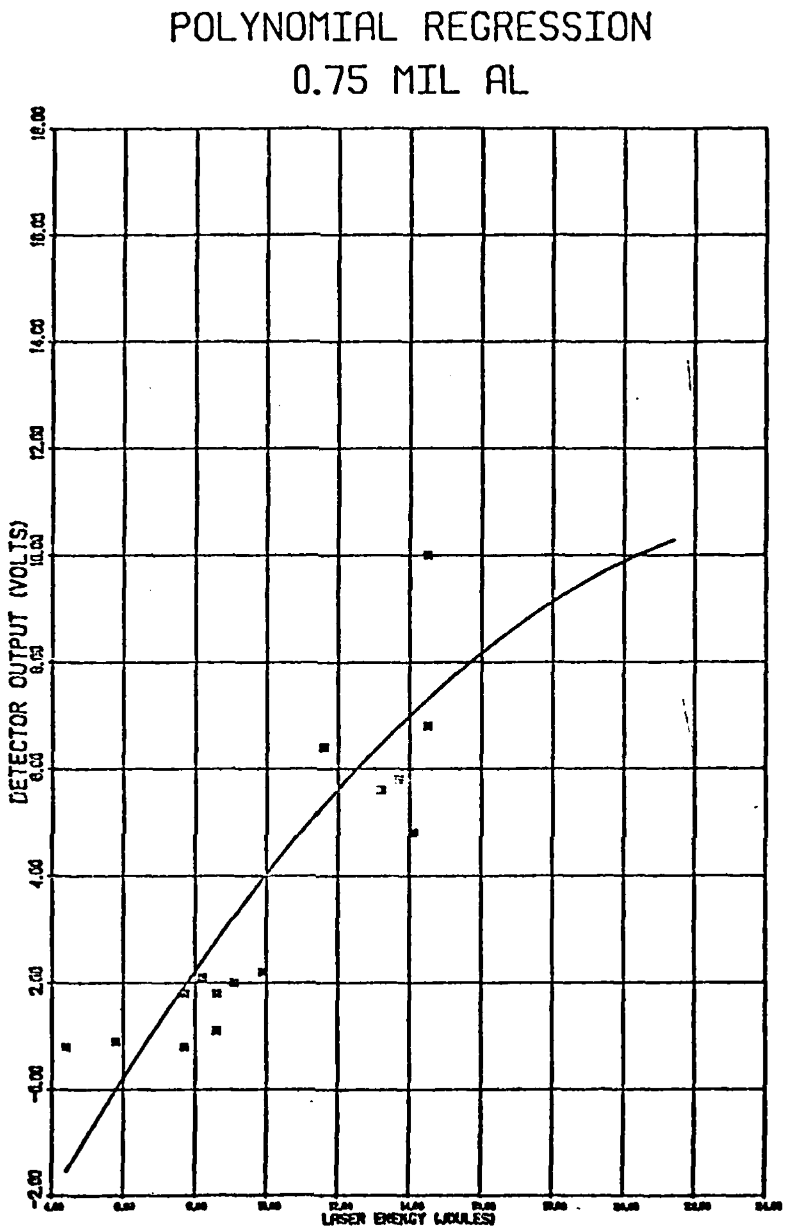


Figure 5. FPM Output vs. Laser Energy

APPENDIX A

LIST OF STUDENTS AND PROJECTS PARTIALLY SUPPORT BY GRANT

1. David Brower, "Construction of a U.V. Ionized CO_2 Laser" (Undergraduate Project).
2. Matt Lambert, "Wave-Guide Laser" (Undergraduate Project).
3. Kenjiro Takeshita, "Numerical Calculations of Exploded Wire Plasmas" (Graduate Project).
4. Don Kania, "CO_2 Laser Heating of an Aluminum Exploding Wire Plasma" (Ph.D. thesis).
5. Susan Wojtovicz, "A Cold Cathode, Soft X-ray Source" (M.S. Project).
6. Ronnie Sheppard, "X-ray Detectors for Laser Plasma Experiments" (Undergraduate Project).
7. Scott Texter, "Time Resolved X-ray Pinhole Camera" (Undergraduate Project).
8. David Hassinger, "Nanosecond High Voltage Pulser for Time Resolved X-ray Photography" (Undergraduate Project).
9. Don Kania, "X-ray Imaging of an Aluminum Exploding Wire Plasma" (M.S. Thesis).

APPENDIX B

PAPERS AND ARTICLES

1. "Intensity Dependent Transmission of 10.6μm Radiation Through A Cold Overdense Z-Pinch Plasma", J. G. Ackenhusen and D. R. Bach, Bull. Am. Phys. Soc. 22, 1205 (1978).

2. "CO_2 Laser Heating of an Aluminum Exploding Wire Plasma", D. Kania and D. R. Bach, Bull. Am. Phys. Soc. 25, 849 (1980).

*3. "Holographic Interferometry of a High Energy Density Exploding Lithium Wire Plasma", P. D. Rockett and D. R. Bach, Journal of Appl. Phys. 50, 2670 (1979).

*4. "Interferometric Characterization of Density Dynamics of an Ultradense Z-Pinch Plasma", J. G. Ackenhusen and D. R. Bach. J. Appl. Phys. 50, 2623 (1979).

*5. "Laser Driven Hydrodynamic Perturbation in an Overdense Z-pinch Plasma", J. G. Ackenhusen and D. R. Bach, J. Appl. Phys. 50, 2623 (1979).

*Note: Papers and articles marked by (*) were partcially supported by the National Science Foundation and The University of Michigan as well as the U.S. Air Force Office of Scientific Research.

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Leonard, T. A., 1972, "Laser Interaction with a High Density Lithium Plasma", Ph.D. Thesis, University of Michigan.

Pronko, J. G., "Temporal Characteristics and Saturation Effects of Organic Scintillators to Low-Energy X-rays", Nuclear Instrumentations & Methods

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